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The Behavior of Haunch Beam-Column Under Loading-Unloading Scheme

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The Behavior of Haunch Beam-Column Under Loading-Unloading Scheme

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Abstract

This research studied the haunch beam-column responses subjected to monotonic and loading-unloading scheme. Experimental investigations were conducted on conventional and geopolymer concrete haunches with identical compression strengths. The influences of the loading-unloading situation to energy dissipation, load-deformation behavior, failure mode, residual deformation, and formation of plastic hinges through the reinforcement yielding mechanism were analyzed. It was found that the differentiation in haunch materials has a negligible influence on the performance of the joint. The loading-unloading protocol had a slightly negative impact on the member's load carrying capacity, which was less pronounced for the geopolymer haunch. Further, the loading-unloading state resulted in a monotonic strength degradation and deviation in failure mode. A surge in energy dissipation was detected due to plastic hinge formation and concrete crushing. The experiment was accompanied by a finite element model utilized to evaluate the response of the haunch's concrete strength to the load-deformation response. The research concluded that a concrete haunch significantly improves the performance of a structure regardless of the haunch material. Moreover, the haunch's compression strength did not influence the overall behavior of the

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1. Introduction

External strengthening becomes necessary when an enhancement in load carrying capacity is required [1, 2, 3]. It is an excellent method for structural conservation with minimum interference to the existing structure. One method for reinforcing a monolithic concrete beam-column joint is by constructing a haunch attached to the column and beam face at the joint. In a strong-column-weak-beam frame, this haunch shifts the formation of the plastic hinge away from the column's face, impacting the overall performance positively. The weakness of this design is that stirrup-spacing tends to be larger the farther away from the column's face. Hence, the confinement provided by these stirrups to the concrete is reduced, and the free distance of the reinforcing steel increases, enhancing the risk of buckling.

In the field, a structural system is subjected to a variation in loading protocols. While bending moments due to gravity loads are predetermined and one-directional in nature, horizontal loads create reverse-signed strain in the flexural member. However, the curvature at the direction of gravity loads in combination with horizontal loads is always more pronounced. This research looked into the influence of loading-unloading scheme on geopolymer and conventional concrete haunch beam-column joints. The structural members have identical dimensions; the geopolymer and conventional concrete haunch strengths were set to be constant and approached the strength of the frame. The study evaluated the effectiveness of this geopolymer haunch. A numerical finite element model (FEM) was constructed and validated to the load-deformation response and crack pattern of the experimental tests. By assuming a full bond between the haunch and beam-column joint, the model was utilized to simulate the influence of the haunch's concrete strength on the load carrying capacity behavior.

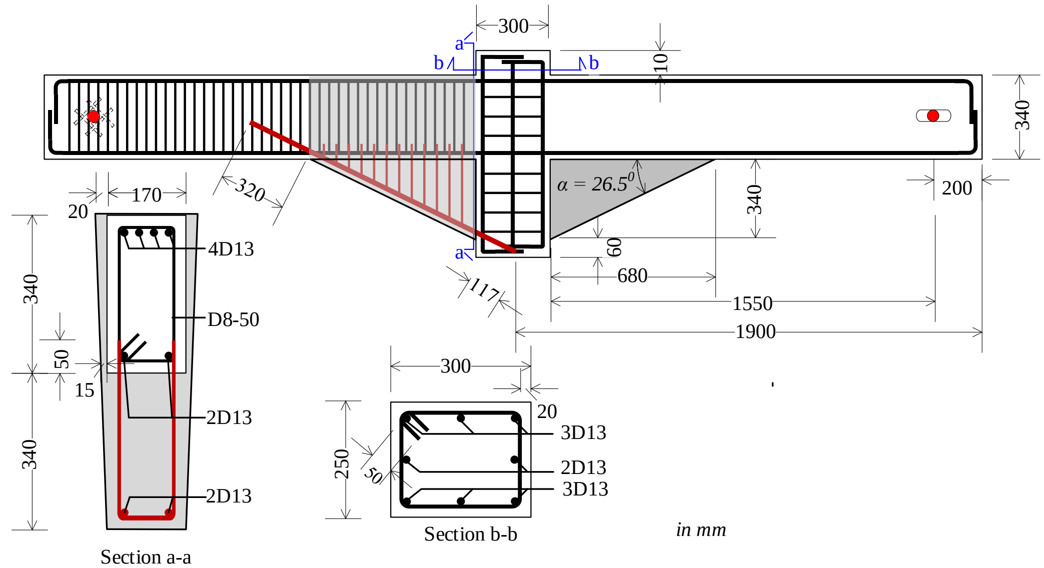
2. Research Significance

Concrete elements degrade in time, and an increase in load carrying capacity demand could lead to the demolishing of structures. Demolishing has, in many ways, a negative impact on the sustainability and green concrete aspect since concrete recycling options are limited. The assembling of a haunch significantly improves the performance of a beam-column joint and the overall structure. When the haunch is constructed using non-cement-based concrete, i.e., geopolymer concrete, the strengthening scheme supports the green concrete aspect due to reduction of ordinary Portland cement use.

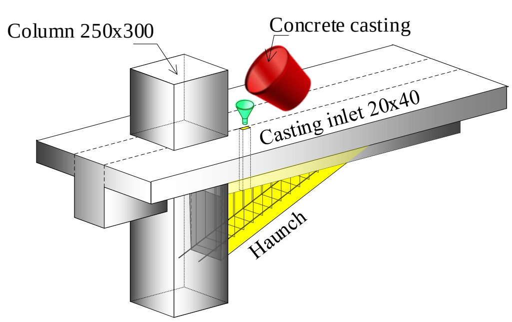
While the monotonic responses of this haunch have been investigated in-depth [?], no information is available on the behavior at loading-unloading state. Moreover, better insight into the failure process of such haunches needs to be studied comprehensively as input for improving the design criteria of concrete haunches in general. The importance of this research is to present information on the usefulness of geopolymer haunches while developing a relationship between the haunch concrete strength and the load carrying capacity behavior through the construction of a finite element model. Additionally, this study contributes knowledge on monotonic degradation, energy dissipation, mode of failure, and the behavior of the member's compression and tensile reinforcement due to the presence of the haunch under loading-unloading sequence.

3. Methods and Materials

The flexural specimen has a length of 1.55 meters and was designed to carry gravity loads. A symmetrical configuration was used to represent the internal beam-column joint in a frame. The haunches were constructed at a later stage to constitute the external strengthening system in the field. Figure 1a illustrates the externally reinforced beam-column joint used in this research work. The haunch was fabricated using a highly flowable concrete mix [4, 5, 6, 7, 8] since the space between the structural elements and this haunch was extremely narrow measure, only 20 mm. The concrete was poured through a hole drilled in the plate, as seen in Figure 1b. The conventional and geopolymer concrete mix had a horizontal flow of 500 mm and 650 mm, respectively. The beam and column, representing the original structure, had a concrete strength of 31 MPa, while the geopolymer and conventional concrete had a 28-day cylinder compression strength ranging from 31.1 MPa to 31.5 MPa. Steel bars with a diameter of 13 mm in combination with stirrups of 8 mm diameter were used to create better integrity between the haunch and the joint. The ultimate and yield stresses were 468.5 MPa and 363.4 MPa for the reinforcement and stirrups, respectively. The reinforcement yield strain was recorded at 0.00205 mm/mm. The haunch was designed to withstand the shear stresses in the member, while based on previous research work, the interface bond between the beam-column joint and the haunch was improved by roughening the concrete surface with grooves to ensure flexural failure [9, 10].



(a) Haunch details



(b) Construction method

Figure 1: Haunch beam-column joint

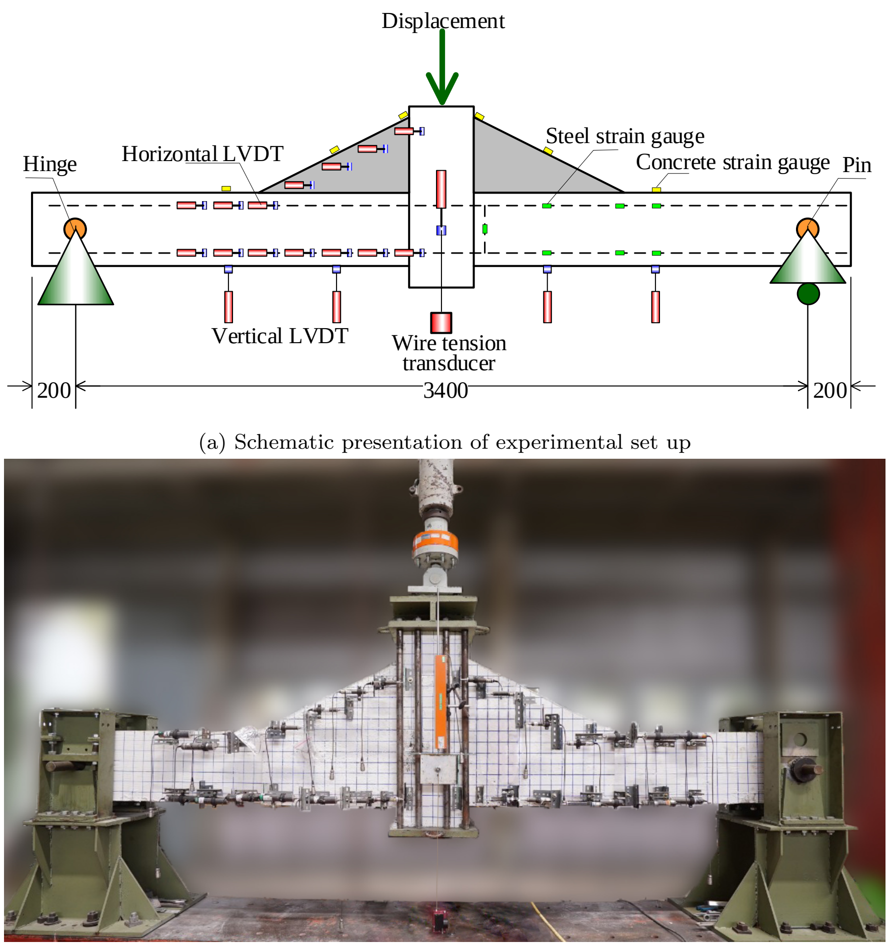
In an actual frame, the beam at a joint is subjected to a negative bending moment due to gravity loads. The haunch in this study is therefore situated in the compression area of the composite structure. The supports at the ends of the specimen were designed to ensure a perfect pin and hinge response. A sufficient stiff member was constructed at the center, representing a monolithic column. The structure was designed to be failed due to the formation of a plastic hinge at the beam, in accordance with the weak-beam-strong-column theory.

Two full scale specimens were prepared; one conventional concrete haunch denoted BC, and another geopolymer haunch denoted BG. The haunch had a dimension of 340 x 680 mm, and an angle of 26.5°. Both specimens were tested simultaneously and all data was recorded for further analysis. The members were subjected to a monotonic loading sequence and a loading-unloading protocol of 10 cycles. The incremental testing procedure was displacement-controlled, where every loading cycle was repeated three times, from which the average was taken representing that particular cycle. Subsequence to one unloading cycle, the residual deformation was set to zero before the following loading cycle was applied. The cycles were conducted with a loading rate of 20 mm/seconds for the loading and unloading stages.

3.1. Experimental research

To simulate the monotonic and loading-unloading state, a column-like element was constructed at the center point, representing a frame's internal beam-column joint. The column was made sufficiently stiff so that a strong-column-weak-beam condition was created, ensuring the plastic hinge formation at the beam. For prismatic members, the plastic hinge is located at the column's face, where the tensile strains due to bending are at maximum [11, 12]. In an actual structure, the beam is subjected to a negative bending moment due to gravity loads. To resemble this negative bending moment, the specimen was turned upside down; a downward load was applied at the column creating a positive bending moment as seen in Figure 2. The haunch was subjected to compression stresses and strains. Figure 2 also represents the loading set-up and the location of precision instruments. Vertical LVDTs (SDP-100C; SDP-300D with a sensitivity of $50\text{x}10^{-6}$ strain/mm and $33\text{x}10^{-6}$ strain/mm) and horizontal LVDTs (CDP-25; CDP-50 with a sensitivity of $500\text{x}10^{-6}$ strain/mm and $200\text{x}10^{-6}$ strain/mm) were used to monitor the vertical and horizontal deformations of the member, while a load cell recorded the load. Strain gauges (FLA 5-11, with a gauge length of 5 mm and resistance of 120 Ω) were situated at the tensile and compression rebars, while the concrete compression strain was measured using PL-60-11, with a gauge length of 60 mm and resistance of 120 Ω to determine the strain state of the steel and concrete with respect to the load.

The horizontal LVDTs were utilized to securely monitor the curvature of the member and haunch during testing. Visual inspection was performed to identify the first cracking of concrete, the crack propagation process and the development of the specimen's overall cracking pattern. The failure mechanism was carefully investigated, where the failure mode was determined based on the observation and validated by the data recorded using the data logger.



(a) Schematic presentation of experimental set up

(b) Actual specimen

Figure 2: Experimental set up and precision instruments

3.2. Finite element modeling

A FEM was constructed for simulation purposes. The FEM was designed as a two-dimensional plane. The concrete was considered nonlinear, the stress-strain constitutive relationship generated from 150 by 300 mm cylindrical test specimens produced at the time of casting, based on the fib 2010 Model Code and incorporating the effect of loading-unloading on concrete [13, 14, 15]. The reinforcement behavior was modeled using a multi–linear relationship from the steel tensile test results [16, 17]. Further, for modeling the fracture energy, the concrete behavior was represented by the total strain-based crack method that follows a smeared approach. The modified compression field theory was accessed as the stress-strain material model [18, 19, 20]. Full-bond compatibility between compression steel reinforcement, stirrups, and concrete was considered [17], while the fib 2010 bond-slip model was used for the tensile reinforcement. The bond between the joint and the haunch was simulated as fully bonded up till failure. The concrete was modeled as a two-dimensional isoparametric eight-node element, whereas the steel reinforcement was modeled as a truss element.

In order to ensure that no failure occurred at the supports, the member's thickness in this area was increased in the FEM, whereas for the experimental specimen, addition steel reinforcements were constructed surrounding the hinge and pin. A sensitivity analysis was performed to determine optimum meshing, while the loading increment followed the displacement-controlled procedure of the experimentally tested specimen. The model generated the load-displacement response, crack pattern, and localization of plastic hinge formation. The results were validated by the experimental data. The model was then used as tool to simulate the influence of the haunch's compression strength on the load-deformation response of the reinforced joint.

4. Result and Analysis

4.1. Experimental research

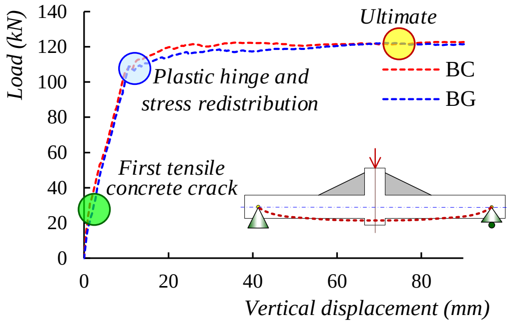
Figure 3a and 3b show the load-deformation response of the members' BC and BG under monotonic loading [21] and loading-unloading scheme. As can be seen in Figure 3a under monotonic loading, the differentiation in material, geopolymer and conventional concrete, has little impact on the load-displacement behavior and load carrying capacity. Generally, the conventional concrete haunch BC demonstrated moderately better performance with a 25% higher initial stiffness and around 2% - 4% better load carrying capacity subsequent to yielding compared to BG. The geopolymer haunch also resulted in a strain energy dissipation reduction of 2.4%. These relatively low values depict that the geopolymer haunch performed remarkably good when compared to the conventional concrete haunch.

Figure 3b represents the loading-unloading sequence of BC and BG. The dots denoted the maximum load increment of each cycle and were used to construct the backbone curve [22, 23]. Information concerning the residual deformation (Figure 3c) and energy dissipation of each cycle (Figure 3d) were also extracted from these data. The specimens BC and BG exhibited similar behavior in terms of ultimate loading, residual deformation, and energy dissipation. The residual deformation followed a convex quadratic pattern with very moderate residual deformations and a graduation of around 0.4 mm at the first three cycles. At the 4^{th} cycle, the tensile reinforcement yielded, and the crack propagation reduced the section stiffness resulting in rapid deterioration. This was reflected by the steep increase in residual deformation of the member, reaching a graduation of 4 mm to 16 mm at the final cycles. Yielding of the compression reinforcement and crushing of concrete at the haunch-tip additionally contributed to this significant increase in residual deformation.

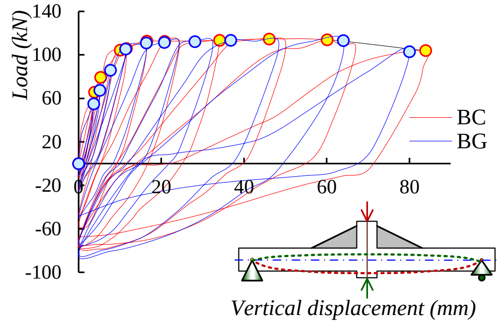
The energy dissipation of each cycle is seen in Figure 3d. Between the 4^{th} and 5^{th} cycle, a sharp increase is detected, coincides with the formation of the plastic hinge and propagation of the cracks in the tensile zone. Between the cycle 5 and 6, another significant surge was detected. This could be explained as a result of the hysteresis and damping energy release due to concrete crushing and steel yielding in the compression area [24].For presentation purposes, the individual energy dissipation per cycle was presented up to the 6^{th} cycle. The accumulation of the energy dissipation is shown by the curved lines.

Comparing these data, it is underlined that the material of the haunch has little to no effect on the beam-column joint response under monotonic and loading-unloading situation. The conventional concrete haunch BC has a slightly better performance compared to BG.

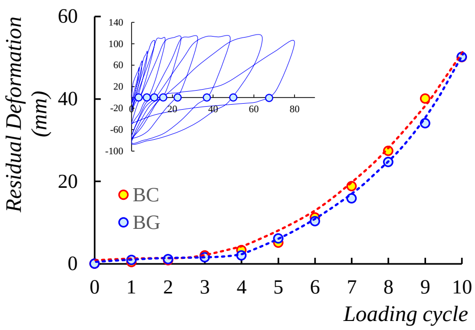
In order to study the overall influence of loading-unloading scheme, the backbone representing the most extreme loadings at each cycle was determined and connected [23, 22, 25]. The loading-unloading protocol resulted in a strength degradation subsequence to reaching of ultimate load [26]. The load-displacement response under monotonic versus loading-unloading backbone is seen in Figure 4a. Table 1 represents the loading levels at first



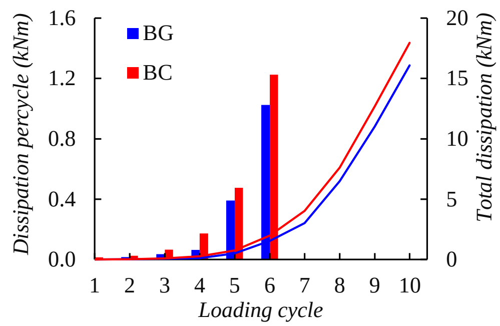
(a) Monotonic loading



(b) Loading-unloading



(c) Residual deformation



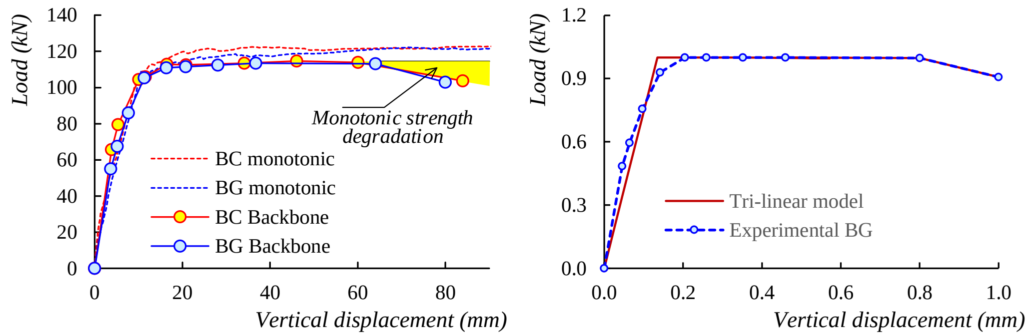
(d) Energy dissipation per cycle

Figure 3: Responses under monotonic and loading-unloading sequence

cracking, yielding of the tensile steel (the formation of the plastic hinge), and failure. The loading-unloading situation decreased the load levels under all conditions; first cracking, the formation of plastic hinge, and at ultimate around 4% to 10% to the monotonic loading. The geopolymer haunch was slightly less sensitive to this reduction.

4.2. Monotonic strength degradation and residual deformation behavior

One important phenomenon was observed while examining the joint's behavior under monotonic loading and loading-unloading condition. The loading-unloading state created a softening branch subsequence to reaching the ultimate load. This monotonic strength degradation was a result of interaction between a number of factors, i.e., loading repetition [23, 22], reverse sign strain in the steel members, beam, arch, and truss action, and stress redistribution after each cycle [27, 28]. The behavior of the backbone curve for the haunch beam-column joint is, therefore, best represented by a tri-linear curve with a descending branch [29, 30, 31]. The reinforced backbone tri-linear model based on the concept of [31] is presented in Figure 4b. The load response was normalized to the ultimate load, while the displacement was normalized to the ultimate displacement. It is demonstrated that the model closely approached the backbone curve of the loading-unloading protocol, including the descending branch of the curve.



(a) Strength degradation

(b) Tri-linear model

Figure 4: Monotonic versus loading-unloading

Table 1: Load level comparison

Specimen	Load (kN)								
	First crack			Plastic haunch formation			Ultimate		
	Monotonic	Loading-Unloading	Deviation	Monotonic	Loading-Unloading	Deviation	Monotonic	Loading-Unloading	Deviation
BC	31.0	29.4	-5%	107.0	100.0	-7%	122.7	114.6	-7%
BG	34.0	32.6	-4%	107.7	104.5	-3%	122.3	113.5	-7%

4.3. The failure mechanism

Due to gravity loads, the beam-column joint in a frame is subjected to a negative bending moment. The haunch is situated in the compression zone of the member. The displacement-controlled protocol created reversed-signed strains in the concrete and steel reinforcement and the interface between the haunch and the joint. During the loading process, the deformation after every cycle was normalized to zero, creating small but not neglectable tensile strains in the haunch area. The integrity between the haunch and the beam-column joint was sustained by the bond between the haunch and the joint and the reinforcing steel. The weakest part of this assemblage becomes the section at the haunch tip. The failure mode was securely monitored and is as follows (Figure 5 and Figure 8a).

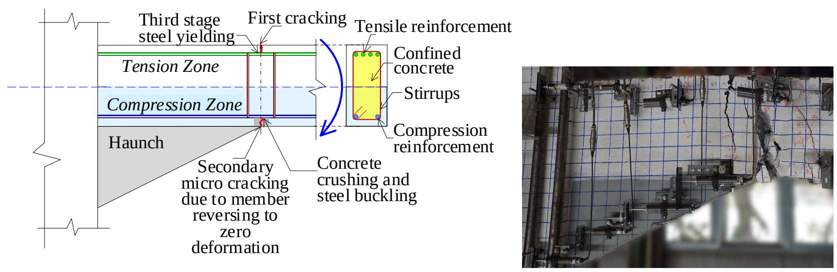
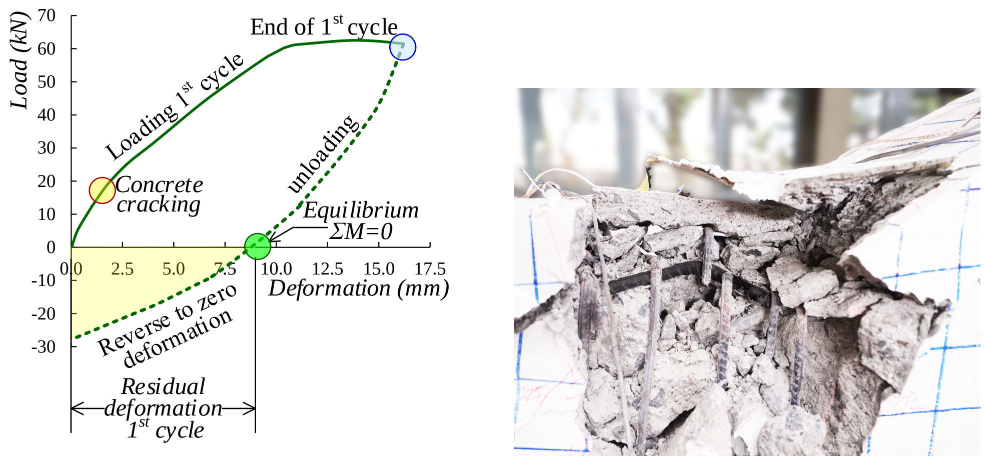


Figure 5: Failure mechanism

The first crack appeared in the tension zone of the beam, in line with the haunch-tip. A permanent residual deformation resulted after unloading, and forces equilibrium was created within the concrete and steel elements (Figure 6a). As the steel was in the elastic zone, this sequence did not impact on the compatibility between the reinforcement and concrete. Reversing to zero deformation of the member created tensile strains in the compression reinforcement and concrete and compression strains in the tensile reinforcement. The next cycle widened the existing crack and increased the residual curvature of the beam. When this curvature generates residual strains exceeding the ultimate concrete tensile strains, micro-cracks occur in the concrete compression zone upon reversing to zero deformation of the member. The crack propagation in the tensile and compression fibers was restrained by the confined concrete area within the boundaries of the stirrups. Due to this confinement, the joint could still carry substantial loading, especially since the compression and tension rebars have sufficient strain energy reserves. Compatibility of the haunch was maintained throughout the overall cycles due to the good bond between haunch and joint and the presence of reinforcing steel.

As loading stages progressed, the tensile reinforcement yielded, resulting in large deformations. Finally, due to the extensive strains in the compression zone, the concrete in compression at the haunch-tip was crushed. Depending on the stirrup spacing, the following failure stage is marked by either yielding or buckling of the compression reinforcement. In this study, the latter was observed (Figure 6b).

The presence of stirrups at the haunch-tip is proven of cardinal importance. The stirrups in a haunch beam-column joint indirectly prevent the



(a) Loading sequence and force equilibrium

(b) buckling of compression reinforcement

Figure 6: Loading mechanism and reinforcement buckling

propagation of cracks through the confinement action and prolong the buckling of compression reinforcement. Although both members underwent first cracking in the 1^{st} cycle, secondary cracks were detected during reversing to the zero deformation of this cycle's residual deformation. At the 4^{th} cycle, tensile steel yielding occurs, marking the plastic hinge formation. Based on the strain gauge readings, the position of this yielding point could be determined with high accuracy (Figure 7).

The diagram shows the strain development in the tensile steel as the load progressed from the first cracking, yielding, to ultimate condition. The precise position of the plastic hinge was precisely in-line with the haunch-tip; the strain of the steel bar to the left and right of the hinge were below the yield strain. At the first cracking, the strain in the tensile reinforcement was low and within the boundaries of the linear elastic zone. At the ultimate condition, the steel yielding has expanded to a distance of 340 mm, half of the haunch length. It is therefore concluded that between the plastic hinge formation and the ultimate condition, the bond between the reinforcement and concrete had degraded gradually. The compression steel underwent yielding at the 5^{th} cycle upon reversing to zero deformation of the member. This yielding has consequences on the further failure mechanism. First, the concrete in the compression zone failed with losing part of the bond between the steel bar and concrete. The following cycle eventually resulted in buckling of the compression steel reinforcement.

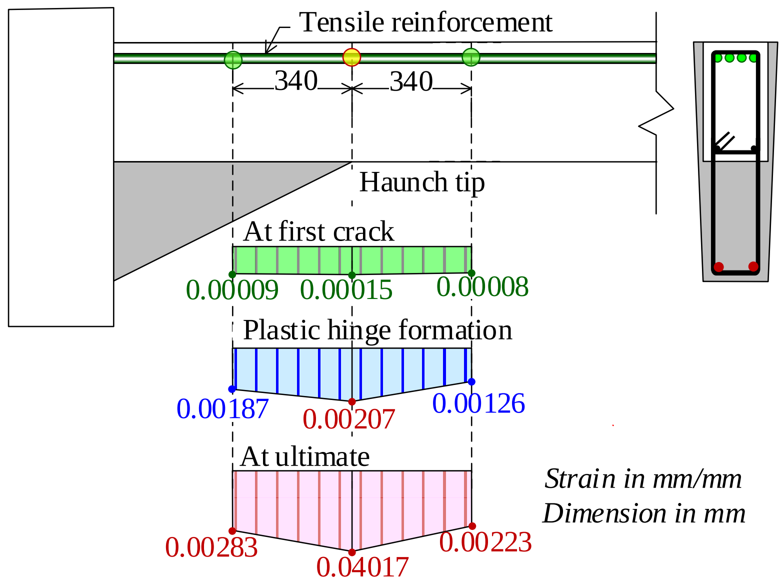
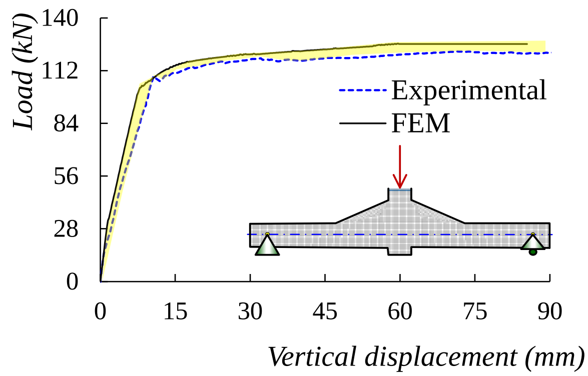


Figure 7: Plastic hinge formation

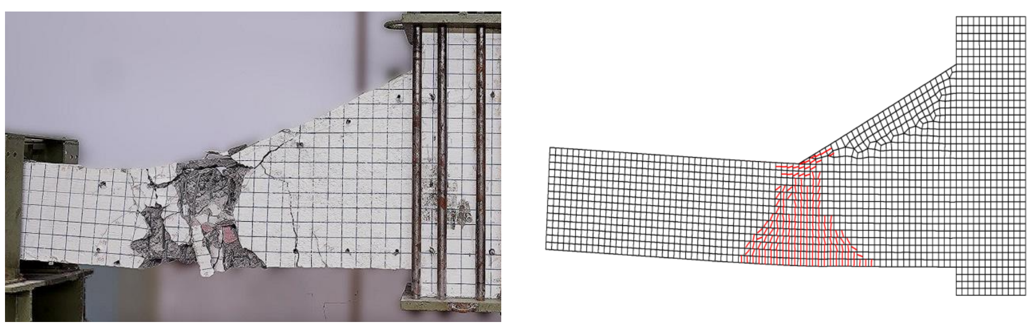
4.4. FEM analysis

Based on the monotonic load-deformation and backbone curves, a FEM was constructed to simulate the influence of the haunch's concrete strength on the member. The model went through a sensitivity analysis to determine the best meshing configuration. Finally, the increment was predetermined to replicate the experimental specimen protocol. Figure 8a represents the load-deformation curves of the FEM versus the experimental test results for BG, Figure 8b demonstrates the predicted crack pattern of the FEM as compared to the experimental test results. The extensive damage in the compression zone and cracking pattern originating from the extreme concrete fibers in compression is clearly shown.

The model perfectly resembles the experimental test data. The FEM initial stiffness overpredicted the stiffness by 20% to 25% to the experimental test results. This exceeding pattern continued after yielding with a milder difference of 2% to 5%. The area is marked in yellow. The strain energy was 5% higher for the FEM. The source of this deviation originates from the assumption that for the compression reinforcement, a full bond was maintained throughout the overall loading procedure. In reality the compression steel yielded, modifying the bond model between the steel and concrete.



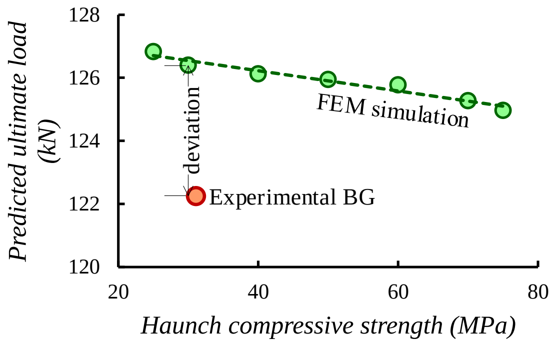
(a) Load-displacement comparison validationg



(b) Crack pattern FEM versus experimental

Figure 8: FEM validation

As proven valid, the model was utilized to simulate the influence of the haunch compression strength on the load-deformation behavior and ultimate load carrying capacity. The data are shown in Figure 9. The model over-predicted the experimental data by 2% to 4%. It is demonstrated that the haunch compression strength has little influence on the ultimate load-carrying capacity. The model was run for haunch strengths ranging from 25 MPa to 75 MPa. The load carrying capacity had a declining linear pattern as a function of haunch strength increase, this behavior is explained due to the increase in stiffness, resulting in a curvature decrease at the haunch-tip. The hysteresis and damping energy became smaller, influencing the load carrying capacity at failure [32, 33, 34, 35].



Specimen	Haunch strength (MPa)	Ultimate load (kN)	Deviation ratio to BG
FEM1	25.0	126.8	1.04
FEM2	30.0	126.4	1.03
FEM3	40.0	126.1	1.03
FEM4	50.0	126.0	1.03
FEM5	60.0	125.8	1.03
FEM6	70.0	125.3	1.02
FEM7	75.0	125.0	1.02
BG	31.1	122.3	1.00

Figure 9: Haunch compression strength simulation

5. Conclusion

The study concluded that the material is not critical to the effectiveness of a concrete haunch. A geopolymer haunch with the exact same dimensions and compression strength as a conventional concrete haunch resulted in the same load carrying capacity of the beam-column joint. The use of geopolymer is therefore strongly encouraged since this material supports the green concrete concept. Due to the narrow spacing, self-compacting concrete mixes are mandatory during construction.

The finite element model simulation suggested that an increase in the ratio of haunch-to-joint strength has a moderate negative influence on the performance of the strengthening system. This outcome is originated from the fact that a haunch with a higher haunch-to-joint strength ratio results in a stiffer assemblage and could thus dissipate less hysteresis and damping energy. Therefore, a strength ratio as low as 2/3 to the joint strength could be used in practice.

When dealing with loading-unloading scheme and reverse-sign strains, the stirrups are important in determining the failure mode. Close spaced stirrups prevent crack propagation as an advantageousness of concrete confinement within the stirrup area and intercept the buckling of compression steel during reloading. Reinforcing steel buckling is particularly prone when the concrete in compression exhibits crushing at the haunch-tip zone. The investigation and analysis of a structure before haunch reinforcement should be conducted with a great care, especially since the haunch relocates the plastic hinge formation away from the column's face, where stirrup spacing might be larger compared to the area near the column.

Loading-unloading sequences for haunch reinforced beam-column joints are recommended up to the compression reinforcement yielding. Afterward to this point, a rapid degradation occurs, and sizeable residual deformation accelerates the collapse procedure of the member. In design, the maximum repetitive load should not exceed the load correlated with the yielding of compression reinforcement. Beam sections with differentiations in compression and tensile reinforcement must be assessed comprehensively to avoid premature failure due to repetitive overloading.

A haunch reinforced beam-column joint is designed to be failed due to the formation of a plastic hinge at the haunch-tip, where the compatibility and integrity between the haunch and the joint should be maintained until failure. This could be achieved by ensuring a good bond between the beam-column and the haunch by creating a rough surface, combined with reinforcement to improve the bond and dowel action between the haunch and the joint.

CRediT Authorship Contribution

Purwanto: Conceptualization, Investigation, Writing - Original Draft, Januarti Jaya Ekaputri: Methodology, Validation. Nuroji: Resources, Data Curation. Bobby Rio Indriyantho: Formal analysis, Writing - Review & Editing, Visualization. Buntara Sthenly Gan: Software, Project administration. Han Ay Lie: Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Paper title: **The behavior of haunch beam-column under loading-unloading scheme**

Highlights:

- A geopolymer haunch is proven equally effective as an external strengthening compared to a conventional concrete haunch with the same compression strength.
- Stirrup spacing in the vicinity of the haunch-tip plays a critical role in the performance and failure mechanism of the assemblage.
- Care has to be taken when a distinguishing steel ratio between the tensile and compression reinforcement exists.
- The finite element model (FEM) concluded that the compression strength of the haunch had little effect on the load carrying capacity.
- A haunch-to-joint strength ratio of 2⁄3 could safely be used.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Semarang, August 26, 2022

Dear Prof. Dyke,
Dear Prof. Meschke,
Dear Prof. Ng,
Dear Prof. Yang,
Dear Editors,

On behalf of all authors, we would like to submit our revised manuscript entitled, "The behavior of haunch beam-column under loading-unloading scheme", for consideration of publication in the *Engineering Structures*.

This study provides information on the concrete industry and design, especially regarding the rehabilitation and revitalization of older structures. The research has brought to light several interesting findings concerning the loading-unloading sequence on concrete haunch beam-column joints. A geopolymer haunch is proven equally effective as an external reinforcing element compared to a conventional concrete haunch with the same compression strength. The geopolymer haunch, on the other hand, contributes to the green concrete concept. The experimental tests showed that stirrup spacing in the vicinity of the haunch-tip plays a critical role in the performance and failure mechanism of the assemblage. Therefore, an in-depth assessment before external haunch reinforcement is of great importance.

The loading-unloading protocol has little influence on the overall structural behavior, as long as the load is within the boundaries of the compression steel reinforcement yielding. Care has to be taken when a distinguishing steel ratio between the tensile and compression reinforcement exists. The accompanying finite element method (FEM) concluded that the compression strength of the haunch had little effect on the load carrying capacity. Therefore, a haunch-to-joint strength ratio of 2⁄3 could safely be used.

The proposed manuscript is our original work and has not been submitted nor published elsewhere. Since this framework covers the experimental study of environmentally friendly building materials namely the self-compacting geopolymer concrete for structural strengthening, it is very likely to be of large interest to the scientist who read this journal.

We would like to thank you for receiving our proposed manuscript. We appreciate your time and look forward to your subsequent response.

Kind regards,

Dr. Ir. Purwanto, M.T., M.Eng.